TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Flight tests of a Grumman Scout (XSF-2) airplane fitted with a Pratt & Whitney 1535 supercharged engine were conducted to determine the effect of engine power, mass flow of the cooling air, and atmospheric temperature on cylinder temperature. The tests indicated that the difference in temperature between the cylinder wall and the cooling air varied as the 0.38 power of the brake horsepower for a constant mass flow of cooling air, cooling-air temperature, engine speed, and brake fuel consumption. The difference in temperature was also found to vary inversely as the 0.39 power of the mass flow for points on the head and the 0.35 power for points on the barrel, provided that engine power, engine speed, brake fuel consumption, and cooling-air temperature were kept constant. The results of the tests of the effect of atmospheric temperature on cylinder temperature were inconclusive owing to unfavorable weather conditions prevailing at the time of the tests. The method used for controlling the test conditions, however, was found to be feasible.

INTRODUCTION

The Committee has investigated the effect of the important engine and cooling conditions on the cylinder temperatures of air-cooled engines with blower-cooled single-cylinder test engines and with multicylinder engines mounted in wind tunnels. The investigation covered the effects of manifold pressure, engine speed, fuel consumption, mass flow of the cooling air, and atmospheric temperature on the cylinder temperatures. The results of some of the tests have been published (references 1 and 2).

It is recognized, however, that in some respects conditions in flight differ from those in the laboratory, especially from the conditions on a blower-cooled single-cylinder test engine where the direction of air flow with respect to the fins may be different and where the effect of turbulence of the air ahead of the engine and the effect of the slipstream are missing. Information as to the extent that the results obtained in laboratory and wind-tunnel tests are applicable to flight being important, a program of flight tests was started to obtain data to supplement those from the laboratory tests of single-cylinder engines.

This report presents the results of flight tests made to determine the effect of engine power, mass flow of cooling air, and air temperature on cylinder temperature.

DESCRIPTION OF APPARATUS

The airplane used in the tests is a 2-place biplane Grumman Scout (XSF-2) supplied by the Bureau of Aeronautics. The airplane is equipped with a Pratt & Whitney R-1535-72 engine, a 14-cylinder 2-row radial air-cooled engine rated at 650 brake horsepower at 2,200 r.p.m. at 7,500 feet altitude. The compression ratio of the engine is 6.7 and the blower speed is 12 times the crankshaft speed.

Tests were made to investigate the cooling of front-row cylinders 4 and 12, the axes of which are horizontal and therefore least affected by the angle of attack of the airplane. The locations of the thermocouples on cylinder 4 are shown in figure 1. Seven thermocouples were located on the head, four on the barrel, and one on the flange. The thermocouple locations were chosen from the 34 locations used as standard in the single-cylinder tests and the numbers correspond to those used in the single-cylinder tests (reference 2). Thermocouples were also located on cylinder 12 at positions corresponding to 6, 12, 14, 15, 19, and 29 to provide a means for checking the results obtained on cylinder 4.

The thermocouple wires were led to a bank of knife switches in the observer's cockpit where the cold junctions of the thermocouples and the potentiometer were located. A mercury thermometer measured the cold-junction temperature. A resistance thermometer was used for measuring the carburetor-air temperature. The atmospheric temperature was measured by an alcohol thermometer located on a strut of the airplane.

A continuously variable Smith propeller from which the stops had been removed was installed to regulate the engine speed.

An N.A.C.A. fuel flowmeter was placed in the fuel line for measuring the rate of fuel consumption. The manifold-pressure gage, altimeter, tachometer, and air-speed head with which the airplane was equipped were retained.

A static-pressure tube was mounted under the cowling ahead of cylinder 4 and another static-pressure tube was mounted behind the cylinder at locations where the velocity head was negligible. Each static tube was connected to one side of an individual pressure cell of a recording manometer. The other side of each of the cells was connected to the static tube of the air-speed meter so that the cells indicated the differences between the static pressures under the cowling and the static pressure in the free air stream. Impact and static-pressure tubes 0.040 inch in diameter were mounted between the fins on the head and the barrel for measuring the cooling-air velocity through the fins. The tubes were located 135° from the front of the cylinder at the positions designated by A_p, A_s, B_p, and B_s in figure 1(b). The subscript p refers to the pitot tube and s to the static tube, which were located in adjacent fin spaces. Each pair of tubes was connected to opposite sides of separate pressure cells in the recording manometer. The deflection of the cell diaphragm measured the velocity head.

The air-speed meter, altimeter, manifold-pressure gage, tachometer, fuel flowmeter, resistance thermometer in the carburetor intake, and manometer pressure cells were calibrated before the tests. A calibration curve of the engine (fig. 2) was obtained from a Navy report on the SR-1535 engine.

METHOD

The tests were made to determine the independent effect of engine power, mass flow of the cooling air, and cooling-air temperatures on engine-cylinder temperature.

Each of these quantities was varied in turn while the others were held constant. During each test the engine speed and the brake fuel consumption were held as constant as practicable. All tests were made in level flight to allow sufficient time for equilibrium conditions to be attained.

The spark plugs of the rear row of cylinders were connected to knife switches located in the observer's cockpit and could be individually grounded, thus providing a means for varying the airplane velocity independent of the power of cylinders 4 and 12. The power of cylinders 4 and 12 was varied by altering the manifold pressure and the engine speed was controlled by means of the controllable propeller.

The power given in the report is on the basis of all cylinders firing as given by figure 2, or 14 times the power of cylinder 4.

The tests of the effect of engine power and of mass flow on cylinder temperature were made at a constant pressure altitude. In the former tests the engine power was varied by varying the manifold pressure while the required number of cylinders were cut out by shorting the spark plugs and the propeller pitch was adjusted to maintain constant airplane velocity and constant engine speed. In the latter tests the manifold pressure was held constant and the airplane speed was changed by shorting the spark plugs. The engine speed was held constant as before by adjusting the propeller pitch. At the beginning of each flight the mixture control was set by the pilot to the full-rich condition and no further adjustment was made.

In the tests to determine the effect of air temperature on cylinder temperature, the variation in air temperature was obtained by flying at various altitudes. At each altitude the throttle, the propeller-pitch control, and the mixture control had to be readjusted to obtain constant engine conditions. The velocity of the airplane was controlled by cutting out the required number of cylinders to give a constant mass flow.

In this report the mass flow is given in terms of the ratio of the true mass flow $V_a\rho_a$ to a standard density ρ_o and its units are the same as those of velocity, where ρ_a is the air density, V_a is the velocity of the air at the point measured, and ρ_o is the density corresponding to standard sea-level pressure and a temperature of 70° F.

The value of ρ_a in $V_a\rho_a/\rho_o$ between the fins should be an average density of the air as it passes around the fins. In this report it is the product of the square root of the air density at the 135° position by the square root of the atmospheric density. The error introduced, however, is negligible.

Tests were made at the following conditions:

	Engine power	Engine speed	Brake fuel consumption	Air stream mass flow $V_a\rho_a/\rho_o$	Pressure altitude
	b.hp.	r.p.m.	lb./b.hp.-hr.	m.p.h.	feet
A - Effect of engine power	varied	1,850	0.53	134	3,200
B - Effect of mass flow:					
(1) First run	417	2,170	.53	varied	4,000
(2) Second run	554	2,170	.46	do.	2,400
(3) Third run	555	2,170	.52	do.	2,400
C - Effect of air temperature	425	2,170	-	111	varied

In the tests of the effect of air temperature, three similar runs were made at conditions substantially as listed in the table. The altitude was varied from 1,000 to 17,000 feet, providing a difference in cooling-air temperature of 40° F. in the first run, 25° F. in the second, 33° F. in the third, and a total difference for the three runs of 53° F. The small change of temperature with altitude was caused by the prevailing cold weather. Difficulty was experienced in maintaining a constant brake fuel consumption as the altitude was changed. In the limited time available for each run an accurate adjustment of the fuel consumption could not be made. The fuel consumption will be shown together with the results of these tests. In future tests a commercial air-fuel-ratio indicator should be provided so that the mixture may be quickly adjusted.

RESULTS

The results for the tests of the effect of engine power on cylinder temperatures are given in table I and are plotted in figure 3 on logarithmic coordinates. The ordinate in figure 3 is the temperature difference between the cylinder and the cooling air. Parallel lines having slopes of 0.38 fitted the test points for all the thermocouples within the limits of accuracy of the data, indicating that the temperature difference between the cylinder and cooling air varied as the 0.38 power of the brake horsepower for constant brake fuel consumption, engine speed, and mass flow of the cooling air.

It will be noted in table I that run 1 was made at a smaller mass flow than the remaining runs. Since, as will be seen later, a given percentage increase in mass flow has approximately the opposite effect on cylinder temperature as the same percentage increase in brake horsepower, this run was corrected to an equivalent mass flow of 134 miles per hour by increasing the brake horsepower in the same ratio as the increase in mass flow. No adjustment of brake fuel consumption was made during the test after the initial adjustment of the mixture control. The brake fuel consumption decreased slightly as the manifold pressure decreased, but the variation was small and probably did not appreciably affect the results. It would be preferable in tests of this nature to maintain a constant air-fuel ratio.

An estimate was made of the indicated horsepower in this test by applying a correction for friction and for the power absorbed by throttling the supercharger. The friction of the engine was obtained from curves given in a recent Navy report on the Pratt & Whitney 1535 engine. It was found that the temperature difference between the cylinder and the air varied as the 0.40 power of the indicated horsepower.

The results for the effect of mass flow on cylinder temperature are given in table II corresponding to the condition B(1) previously given and are plotted on logarithmic coordinates in figure 4. The ordinate in figure 4 is the difference in temperature between the cylinder and the air, and the abscissa is the ratio of the mass flow to the standard sea-level density. Except for thermocouple 17 the exponents for the variation of temperature difference with mass flow on the head group closely about a mean value of -0.39. Thermocouple 17 is probably in error. The exponents for the points on the barrel are more scattered and average to -0.35. The exponent for the flange is -0.23. In this test, as in the previous one, the brake fuel consumption was adjusted in the first run and, although no additional adjustment was made, it remained substantially constant during the remainder of the test.

In the check tests B(2) and B(3), the test conditions were not maintained quite as constant as in B(1) and the results were more erratic. They did, however, show substantial agreement with the results of B(1).

The results for the three tests are listed below:

	Head exponent	Barrel exponent	Flange exponent
B(1). . .	-0.39	-0.35	-0.23
B(2). . .	-.37	-.33	-.17
B(3). . .	-.36	-.40	-.34

The temperatures of cylinder 12 were in most cases lower than those of cylinder 4 and somewhat erratic but the average exponents showed substantial agreement with those obtained on cylinder 4.

Attention is directed to the fact that the change in pressure drop was obtained by varying the airplane speed. Increasing the pressure drop by increasing the opening in the exit of the cowling would have a somewhat different effect on cylinder temperature. The cooling of the front half of the cylinder is produced mainly by air movement or turbulence under the cowling resulting from the velocity of the airplane and this air movement is influenced only slightly by opening the cowling exit. It is evident that, although the temperatures at the rear of the cylinders would increase in a manner similar to that indicated in figure 3, much smaller increases in temperature would be obtained for the front half of the cylinder.

The exponents given in figures 3 and 4 for the variation of cylinder temperature with mass flow and engine power apply for the conditions at which the tests were made. A small variation in these exponents is to be expected with change in test conditions.

The variation of pressure drop across the cylinder ΔP with the velocity in the free air stream, with the velocity between the fins on the head at point A, and with the velocity between the fins on the barrel at point B are shown plotted on logarithmic coordinates in figure 5. The pressure drop and velocities were multiplied by ρ_a/ρ_o. Lines having a slope of 2.0 drawn through the points in figure 5 represent the data with a good degree of accuracy, indicating that the pressure drop varies as the square of the velocity. At the low airplane velocities the points for the variation of pressure drop with airplane velocity deviate from the line, showing that at these velocities the square law begins to break down. This deviation may be caused by the large change in angle of attack of the airplane and by the increased importance of the slipstream at these low velocities. The curves for the variation of the velocity between the fins with pressure drop, as may be expected, are not influenced by these factors. Except for the low velocity range, the velocities between the fins are directly proportional to the velocity of the free air stream.

Figure 6 shows the ratio of the pressures under the cowling to the dynamic pressure q of the free air stream plotted against mass flow. The curves indicate that, for the largest part of the range of airplane speeds, the pressure ahead of the cylinder is about 0.7q and the pressure behind the cylinder is about 0.2q above the free-air-stream pressure. These values fall off slightly at the lower airplane speeds, as may be expected from the discussion of figure 5. The loss in head of 0.3q in front of the engine is high and indicates a poor cowling-nose design. A lower pressure behind the engine would be obtained if the cowling skirt were flared to a greater degree and if the clearance between the baffles and the fins were reduced.

The results of the tests of the effect of atmospheric temperature on cylinder temperature were considerably more erratic than those of the other variables tested. More adjustments were required to maintain the test conditions and, owing to the multiplicity of the duties of the observer, more personal error could be expected in the readings.

An examination of the data for the atmospheric-temperature tests showed that, although the mass flow based on the free air-stream velocity was kept constant, the mass flow between the fins on the head and barrel and the pressure drop across the cylinder varied, the last three items showing fair agreement with each other. It was therefore decided to correct the cylinder temperatures to the same mass flow between fins, using the exponents obtained in the tests of the effect of mass flow on cylinder temperature. The temperatures were also corrected to the same engine power. No correction could be applied for the variation in brake fuel consumption, and the results are in error to the extent that the variation in brake fuel consumption affects cylinder temperature. The brake fuel consumption for each point is shown plotted in figure 7. During the first flight of this series of tests, the fuel flowmeter failed and no values of brake fuel consumption were obtained for several of the tests of this flight. The fuel flowmeter was repaired and functioned satisfactorily for the remainder of the flights.

Owing to the small variation of temperature with altitude, the results of each flight were inconclusive. A larger range in atmospheric temperature was covered and more consistent results were obtained by plotting the results of several of the flights together. These results are also shown in figure 7. The slope of the curves represents the change in cylinder temperature per degree change in air temperature. Similar laboratory tests of a cylinder from a Pratt & Whitney 1535 engine gave average correction factors of 0.83 for the rear spark-plug gasket, 0.77 for the head, 0.70 for the barrel, and 0.60 for the flange.

Experience with these tests indicates that the method used is feasible for obtaining the variation of cylinder temperature with atmospheric temperature and that under more favorable weather conditions than existed in the present tests, better results would be obtained. It is hoped to make further tests when a larger atmospheric temperature gradient exists.

CONCLUSIONS

1. The difference in temperature between the cylinder wall and the cooling air varied as the 0.38 power of the brake horsepower for a constant mass flow of cooling air, cooling-air temperature, engine speed, and brake fuel consumption.

2. The difference in temperature between the cylinder wall and cooling air varied inversely as the 0.39 power of the mass flow for points on the head and 0.35 power for points on the barrel provided that the engine power, the engine speed, the brake fuel consumption, and the cooling-air temperature remained constant.

3. The velocity between the fins on the head and the barrel varied linearly with the free air-stream velocity except in the range of low airplane speeds.

4. The static pressure under the cowling ahead of the cylinder was 0.7q and behind the cylinder was 0.2q for the greater part of the velocity range of the airplane. At low velocities these values fell off slightly.

5. The tests of the effect of atmospheric temperature on cylinder temperature were inconclusive but did indicate that the method used was feasible and that, under conditions giving a greater temperature range with altitude, better results could be obtained.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., October 5, 1936.

REFERENCES

1. Schey, Oscar W., and Rollin, Vorn G.: Cooling Characteristics of a 2-Row Radial Engine. T.R. No. 550, N.A.C.A., 1935.

2. Schey, Oscar W., and Ellerbrock, Herman H., Jr.: Performance of Air-Cooled Engine Cylinders Using Blower Cooling. T.N. No. 572, N.A.C.A., 1936.

TABLE I

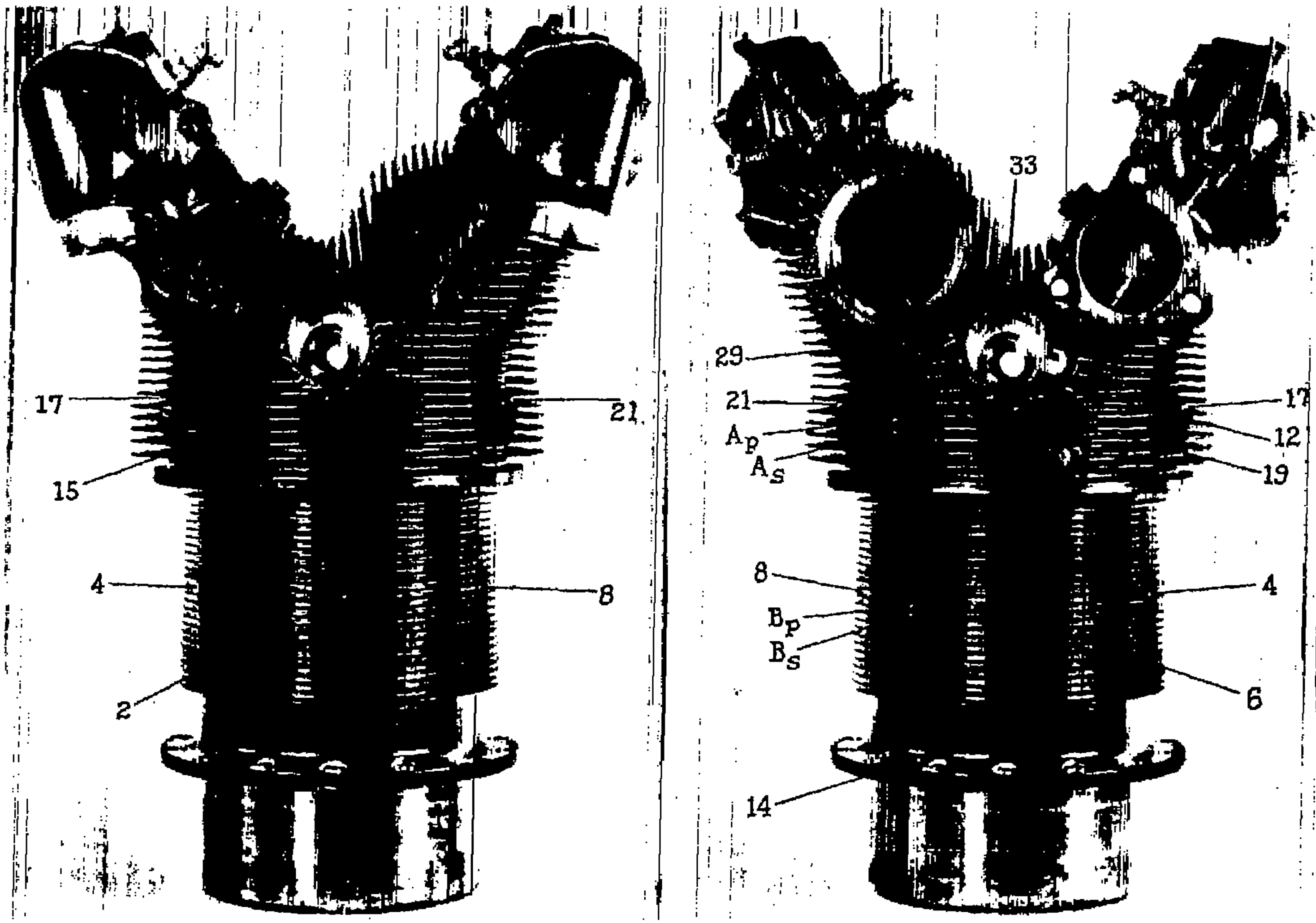
EFFECT OF BRAKE HORSEPOWER ON CYLINDER TEMPERATURE

Run	1	2	3	4
Brake horsepower	536	352	320	262
$V_a\rho_a/\rho_o$, free air stream, m.p.h.	124	134	134	134
Brake fuel consumption, lb./b.hp.-hr.	0.55	0.54	0.52	0.52
Cooling-air temperature, °F.	9.5	11.3	11.3	11.3
$V_a\rho_a/\rho_o$, fins on head, m.p.h.	82.5	92.2	92.2	94.4
$V_a\rho_a/\rho_o$, fins on barrel, m.p.h.	68.2	78.4	78.4	77.6
p/q, front of cylinder	.560	.633	.651	.668
p/q, rear of cylinder	.196	.202	.219	.239
Thermocouple	Difference between cylinder temperature and cooling-air temperature, degrees F.			
2	252	210	197	191
4	257	219	209	200
6	342	307	289	277
8	297	254	243	223
12	515	437	422	393
14	261	241	229	218
15	351	270	258	257
17	271	225	219	211
19	442	372	367	330
21	391	324	319	298
29	498	415	415	380
33	468	389	389	359

TABLE II

EFFECT OF MASS FLOW OF COOLING AIR ON CYLINDER TEMPERATURE

Run	1	2	3	4
Brake horsepower	417	417	417	417
$V_a\rho_a/\rho_o$, free air stream, m.p.h.	159	137	117	99
Brake fuel consumption, lb./b.hp.-hr.	0.52	0.53	0.52	0.55
Cooling-air temperature, ^{o}F.	27.5	27.5	27.5	27.5
$V_a\rho_a/\rho_o$, fins on head, m.p.h.	114.6	-	85.2	70.9
$V_a\rho_a/\rho_o$, fins on barrel, m.p.h.	100.2	-	72.3	59.5
P/q, front of cylinder	.644	-	.667	.511
p/q, rear of cylinder	.205	-	.205	.131
Thermocouple	Difference between cylinder temperature and cooling-air temperature, degrees F.			
2	208	215	217	240
4	223	236	238	258
6	286	298	305	337
8	230	242	258	273
12	416	428	456	504
14	231	236	235	256
15	261	269	292	317
17	230	238	257	298
19	365	377	397	442
21	303	318	340	368
29	400	415	442	485
33	372	388	415	453



(a) Front (b) Rear

Figure 1.- Thermocouple locations on cylinder 4 from Pratt & Whitney 1535 engine.

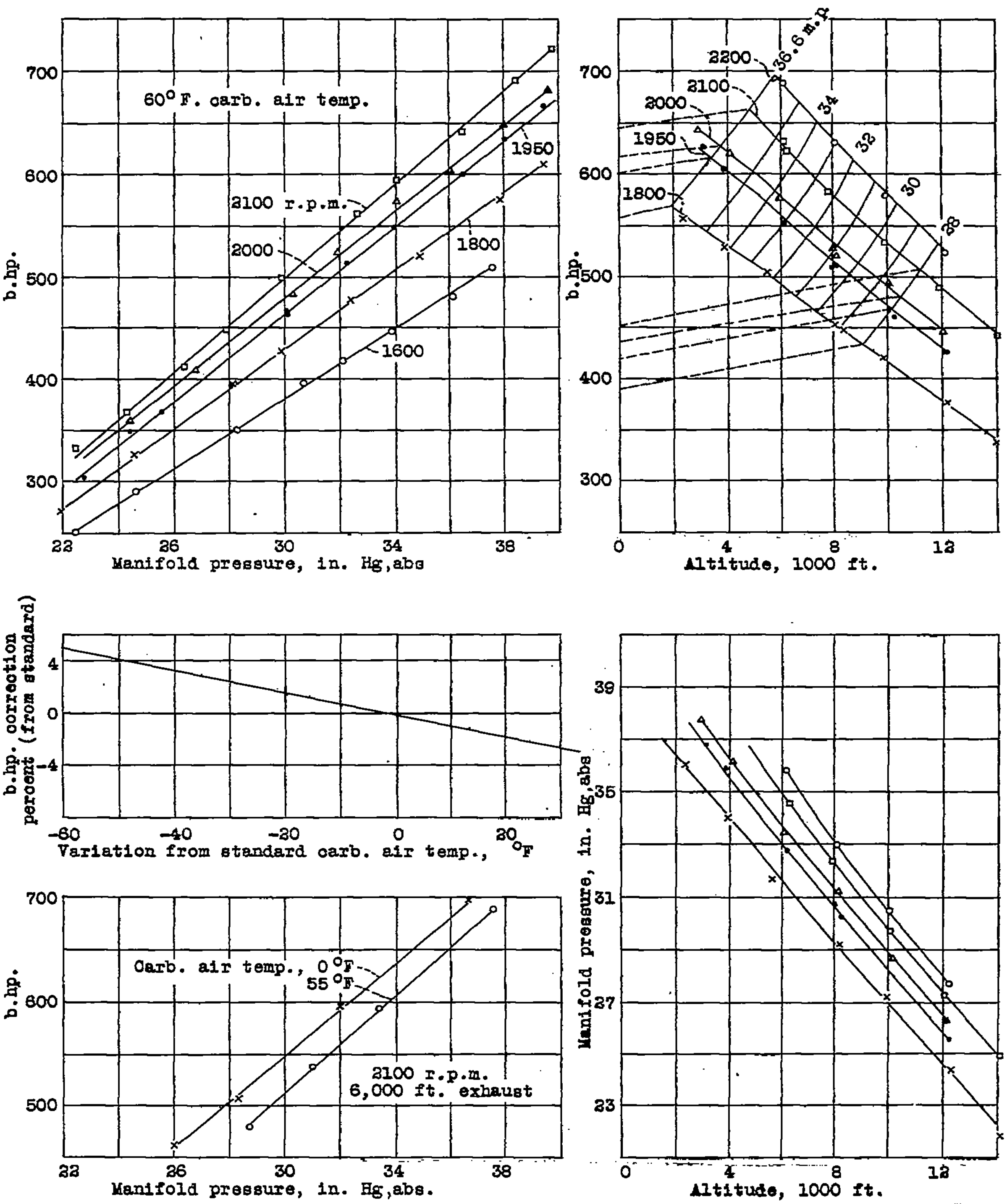


Figure 2.- Calibration of Pratt & Whitney 1535 engine.

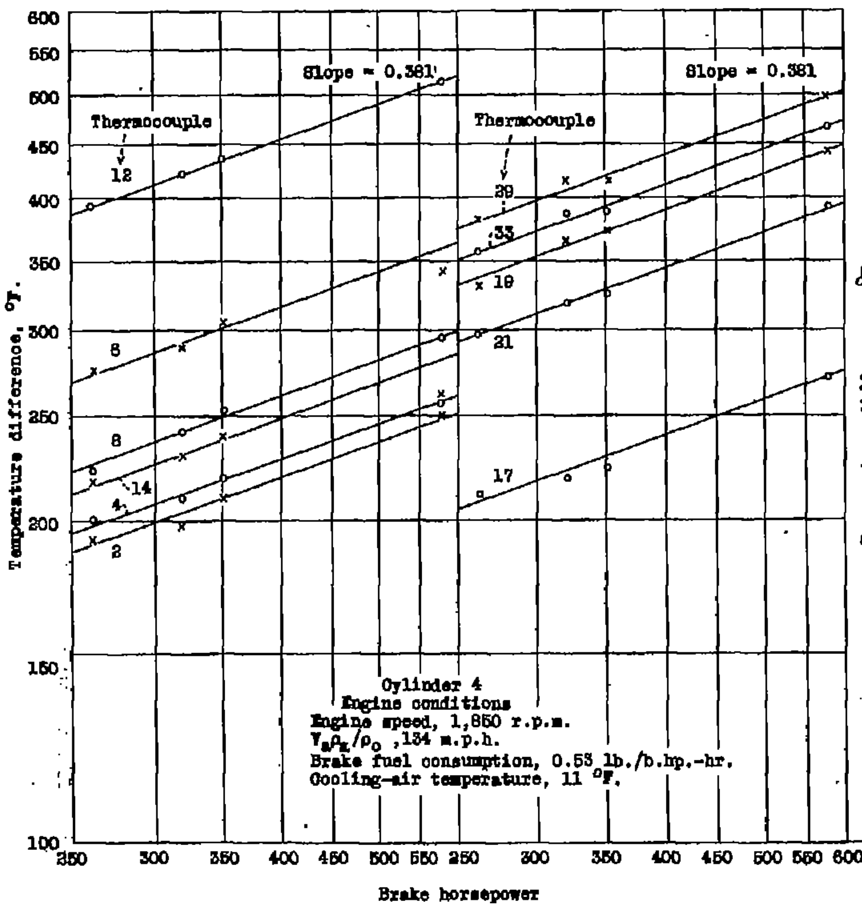


Figure 3.- Variation of cylinder temperature with brake horsepower.

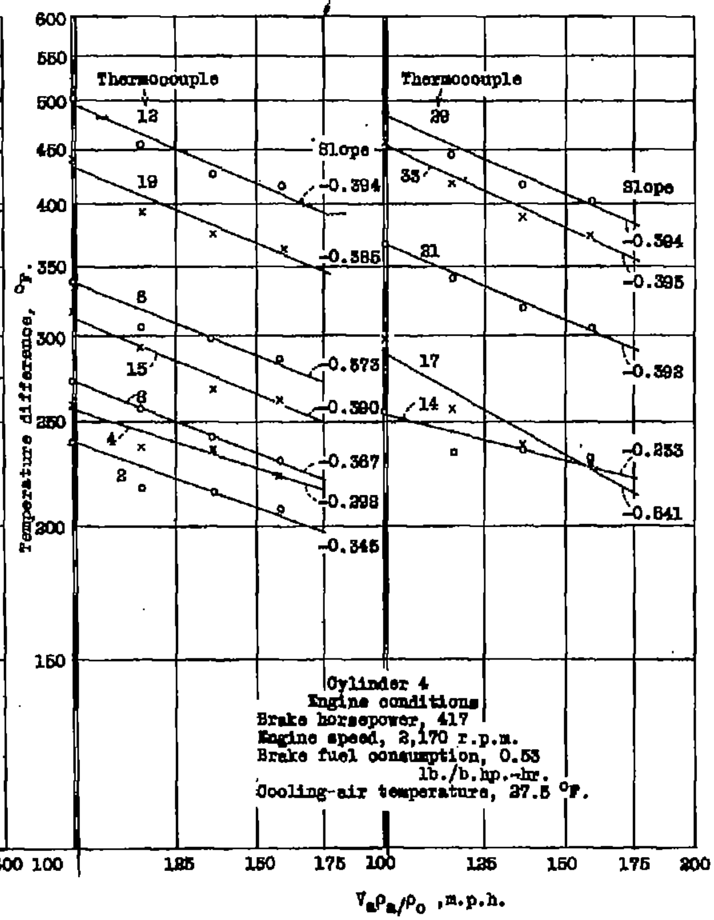


Figure 4.- Variation of cylinder temperature with mass flow of cooling air.

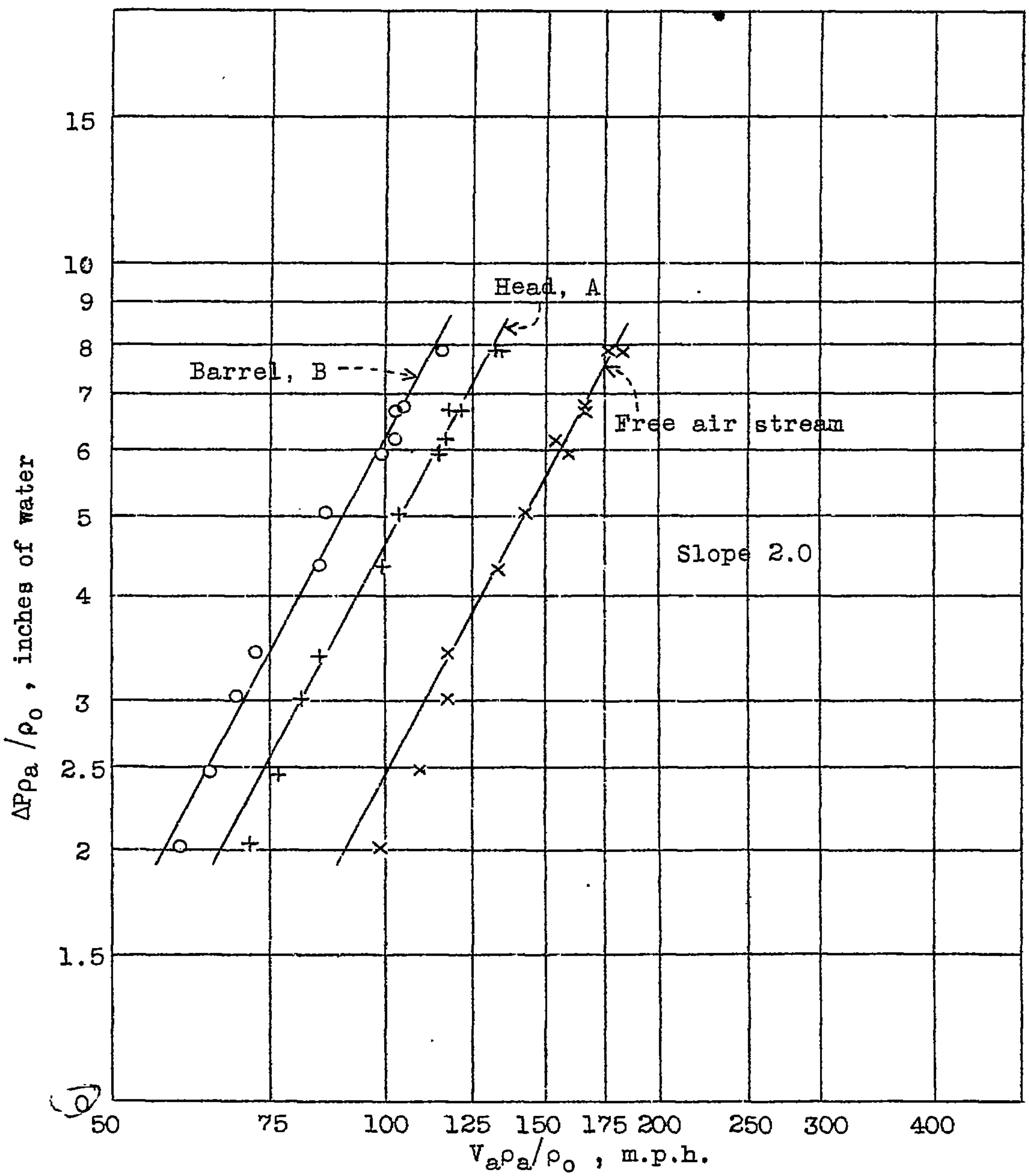


Figure 5.- Variation of pressure drop across cylinder with mass flow between fins and with mass flow relative to airplane.

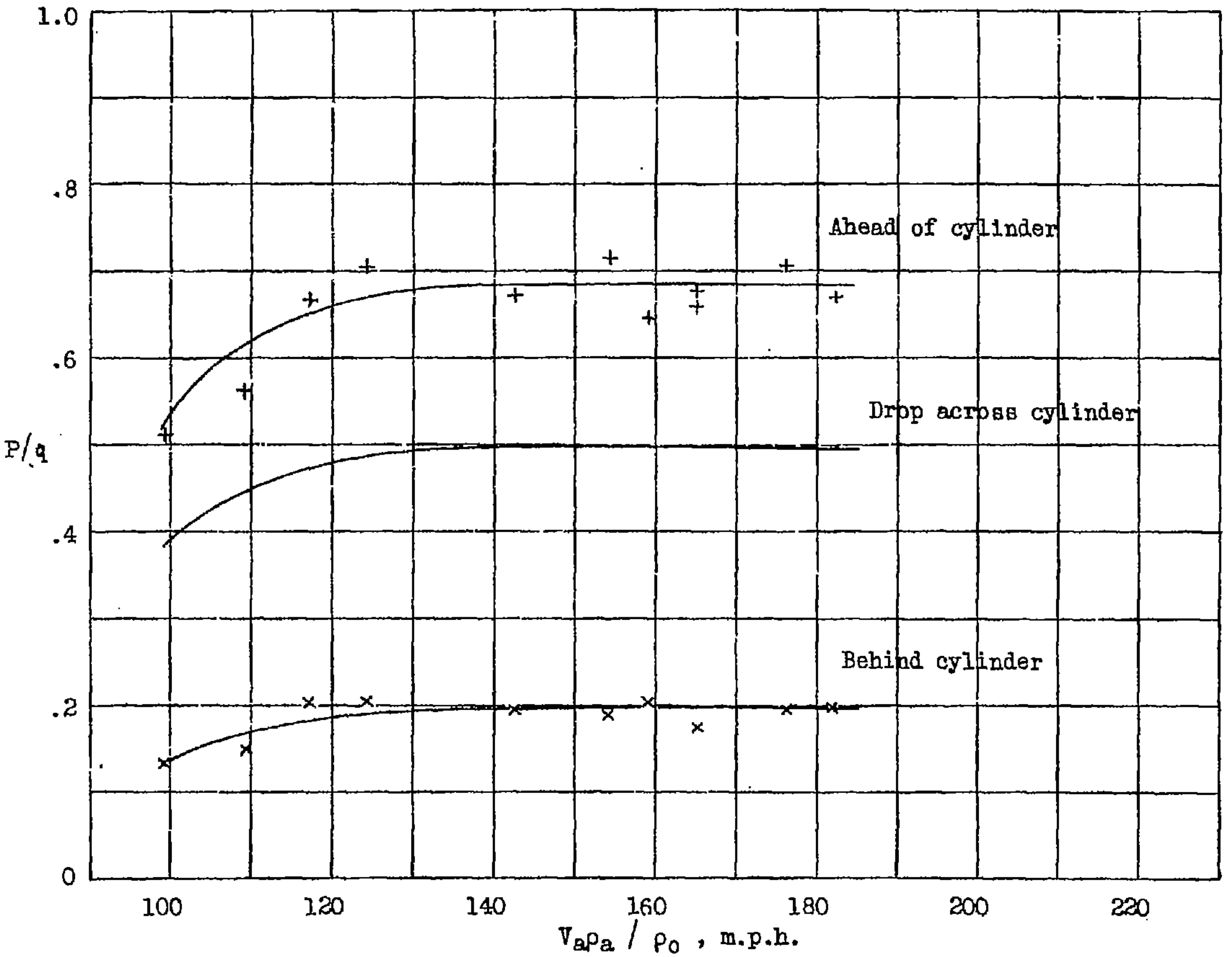


Figure 6.- Variation of ratio of pressure under cowling to dynamic pressure in free air stream with mass flow relative to airplane.

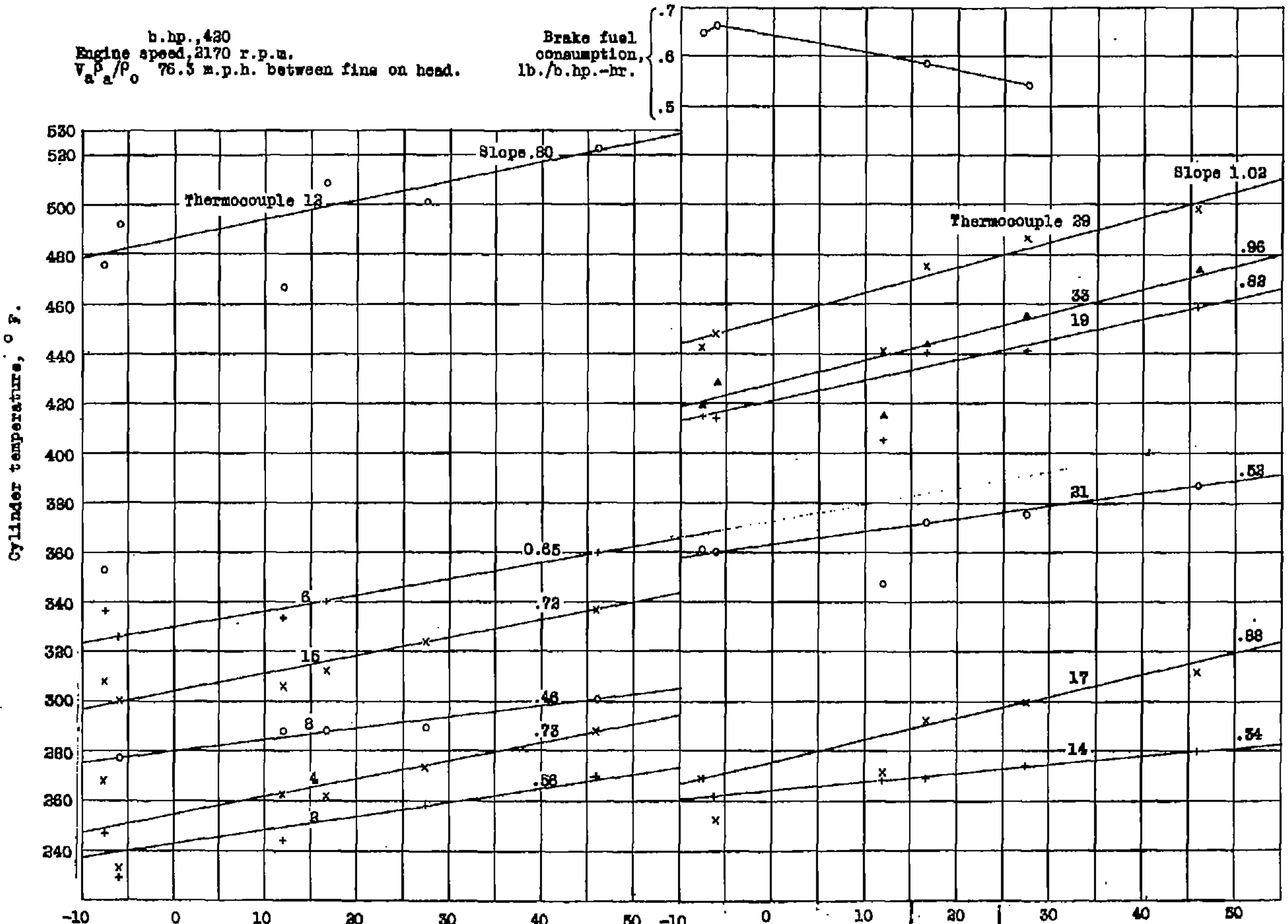


Figure 7.- Variation of cylinder temperature with temperature of cooling air.